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Exploring diversity in soil fertility management of smallholder farms in western Kenya
II. Within-farm variability in resource allocation, nutrient flows and soil fertility status

P. Tittonell [a,b,*], B. Vanlauwe [a], P.A. Leffelaar [b], K.D. Shepherd [c], K.E. Giller [b]

[a] *Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), United Nations Avenue, P.O. Box 30677, Nairobi, Kenya*
[b] *Plant Production Systems, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands*
[c] *World Agroforestry Centre (ICRAF), P.O. Box 30677, Nairobi 00100, Kenya*

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Abstract

Strong gradients of decreasing soil fertility are found with increasing distance from the homestead within smallholder African farms, due to differential resource allocation. As nutrient use efficiency varies strongly along these gradients, such heterogeneity must be considered when designing soil management strategies, aimed at an improved overall resource use efficiency at farm scale. Here, we quantify the magnitude and study the origin of farmer-induced, within-farm soil fertility gradients as affected by biophysical and socio-economic conditions, and investigate farmers' perceptions of such heterogeneity. Farm transects, participatory resource flow mapping, farmers' classification of land qualities, and soil sampling for both chemical and spectral reflectance analyses were performed across 60 farms in three sub-locations (Emuhaia, Shinyalu, Aludeka) representing the variability found in the highlands of western Kenya. Differences between the various field types of a farm were observed for input use (e.g. 0.7–104 kg N ha^{-1}), food production (e.g. 0.6–2.9 t DM ha^{-1}), partial C (e.g. −570 to 1480 kg ha^{-1}) and N (e.g. −92 to 57 kg ha^{-1}) balances and general soil fertility status, despite strong differences across sub-locations. Concentration of nutrients in the home fields compared with the remote fields were verified for extractable P (e.g. 2.1–19.8 mg kg^{-1}) and secondarily for exchangeable K (e.g. 0.14–0.54 $cmol_{(+)}$ kg^{-1}), on average, whereas differences for soil C and N were only important when considering each individual farm separately. Farmers managed their fields according to their perceived land quality, varying the timing and intensity of management practices along soil fertility gradients. Fields classified by them as poor were planted later (up to 33.6 days of delay), with sparser crops (ca. 30% less plants m^{-2}) and had higher weed infestation levels than those classified as fertile, leading to important differences in maize yield (e.g. 0.9 versus 2.4 t ha^{-1}). The internal heterogeneity in resource allocation varied also between farms of different social classes, according to their objectives and factor constraints. Additionally, the interaction of sub-location-specific socio-economic (population, markets) and

* Corresponding author.
E-mail addresses: ptittonell@yahoo.com.ar, pablo.tittonell@wur.nl (P. Tittonell).

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biophysical factors (*soilscape* variability) determined the patterns of resource allocation to different activities. Such interactions need to be considered for the characterisation of farming system to facilitate targeting research and development interventions to address the problem of poor soil fertility.

Keywords: Soil fertility gradients; Farmers' perceptions; Management intensity gradients; Field typology; Local soil quality indicators

1. Introduction

In many farming systems in the tropics, strong gradients of decreasing soil fertility are found with increasing distance from the homestead (Ruthenberg, 1980; Prudencio, 1993). Farmers manage crop and livestock production using organic and mineral nutrient resources, and the net flow of resources is not equal for the various fields belonging to a single farm household (Smaling et al., 1996). Continuous concentration of nutrients in the smaller areas around the homestead, at the expense of nutrient depletion in further and larger fields, coupled with continued export of produce and a lack of external inputs into the farm, leads to an overall negative nutrient balance at farm level (Giller et al., 1997). Differential long-term management of the fields of a farm creates zones or gradients of soil fertility due to concentration of agricultural produce and organic wastes around the homesteads (Scoones and Toulmin, 1999; Smaling et al., 1997).

Giller et al. (2005) and Vanlauwe et al. (2000a,b) have provided preliminary evidence that nutrient use efficiency varies strongly between fields along these gradients of soil fertility within African smallholder farms. Although it may be assumed that soil-improving technologies should be targeted to the more degraded soils as a means for restoration of agricultural productivity, this is often unsuccessful; e.g. soil-improving legumes often grow extremely poorly on degraded land and give little benefit to enhancing soil fertility. The importance of soil fertility gradients in smallholder farms is thus a main research priority within the Nutrient Use in ANimal and Cropping systems – Efficiency and Scales (NUANCES) framework (Giller et al., 2005). The existence of soil fertility gradients within smallholder farms must be considered when designing integrated soil fertility management strategies, aiming at an improved efficiency for the overall nutrient dynamics within the farm system, especially in the context of farming systems in sub-Saharan Africa (SSA), which often have a chronic lack of access to inputs.

Distance from the homestead (home fields, outfields), biophysical discontinuities (termite mounds) and history of use (old hut-site, old kraals, etc.) have been used as criteria to classify within-farm micro-environments (e.g. Mapfumo and Giller, 2001; Carter and Murwira, 1995; Chikuvire, 1998). The sources of variability and factors affecting decisions on soil fertility management can be derived from both the agroecological (biophysical) and the socio-economic environments; the latter having different consequences for farms varying in resource endowment and production objectives (Tittonell et al., 2005b). Variability in soil fertility at farm scale may be associated with topography, soil types, land degradation intensities, sharp physical discontinuities (e.g. rocky outcrops), land-use history or distance from the homestead and livestock facilities.

Methodological tools have also been developed to identify local indicators of soil quality related to permanent and modifiable soil properties by farmers (e.g. Barrios et al., 2001), which can be used to assess farmers' perceptions on soil fertility gradients. Farmers are often aware of the existence of such gradients and use local terms to ascribe different soil quality features to different fields within their farms (TSBF, 2001). Final recommendations on targeting nutrient sources within farms need to be based upon such local soil knowledge systems, given that farmers are unlikely to have access to soil analytical services in the short to medium term in SSA.

The relative role of inherent soil properties in contrast to management-induced effects in creating, maintaining and increasing the magnitude of soil fertility gradients is likely to vary between and within regions. In many West African farming systems differences in soil fertility have been described for fields that are sometimes several kilometres apart. In

populated areas, farm sizes are smaller and the biophysical within-farm variability tends to decrease, but our preliminary observations suggested that soil fertility gradients existed even within farms of less than 1 ha in size consisting of contiguous fields. On the basis of these ideas we proposed two hypotheses, namely:

1. Soil fertility gradients arise from farmers' management of their fields depending on both inherent production potentials and their resource base in terms of land, labour and capacity to invest in nutrient resources.
2. The magnitude of within-farm soil fertility gradients is affected by socio-economic and biophysical factors and will be larger in regions with lower population density and a larger variation in soil types.

This study was designed to (i) quantify the magnitude of within-farm soil fertility gradients as affected by biophysical and socio-economic conditions; (ii) document the factors driving the farmers' decision making processes resulting in farmer-induced soil fertility gradients, and (iii) investigate farmers' perceptions of such gradients.

2. Materials and methods

2.1. Overall approach

The western Kenya region was chosen due to its demographic and agro-ecological characteristics, which are broadly representative of the situation found in other tropical highlands of East Africa (Braun et al., 1997). Background information and tours around the area were used for the selection of representative sub-locations within the region. The sites (Emuhaia, Shinyalu and Aludeka, sub-locations within Vihiga, Kakamega and Teso districts, respectively) were visited and key informants interviewed to develop initial lists of farms to be included in the sample from each place. Farms were first visited to gather socio-economic and biophysical information, which was contrasted with official surveys and previous work in the region and proved fairly representative of the situation found at each sub-location. The information collected was used to construct a farm typology consisting of five different farm types, according to household objectives and resource endowment. A detailed description of the study area, together with the criteria and procedures for farm selection, characterisation and typology definition are presented in Tittonell et al. (2005b).

Most farms in the sample from each sub-location ($n = 20$) were revisited to gather more specific information on management practices and on farmers' perceptions of soil fertility gradients, by means of interviews and a farmer-defined soil quality classification. From each farm type, case-study farms were selected to assess resource allocation patterns and their effect on soil fertility by means of resource flow maps, nutrient balances, soil sampling and laboratory analysis.

2.2. Classifying and measuring within-farm variability

Interviews were conducted in 45 farms (three farms per farm type per sub-location). Questions on the relative importance of the various production activities, and the timing of the farm management practices for the different fields within the farm were put to the farmers. They classified their production units in classes of fertile, average or poor. We walked through each farm along a transect together with the farmer and discussed each field in turn, aided by a map of the farm drawn by him/her. Farmers were also requested to give their criteria underlying this land classification and why crop performance varied among fields. The area of each of the identified units was measured using a GPS. The total area of fertile, average and poor land within each farm and the percentage of each class relative to total farm size were then calculated.

The fields within each farm visited were also classified using a field typology that described resource allocation patterns and internal (within farm) nutrient flows that affect soil fertility (Mapfumo and Giller, 2001). Land use and distance from the homestead were the main criteria to classify field types (e.g. home gardens, remote fields), as maize yields, soil quality indicators and the intensity of management practices were negatively correlated to the distance from the homestead in preliminary research in the region (Tittonell, 2003). Additionally,

the type and number of crops grown, use or destination of the outputs, type and amount of inputs used, timing of crop and soil management activities and sequential order within the farm, average yields obtained, weed infestation levels, and general crop husbandry practices adopted (e.g. plant density) were recorded. Maize yields were estimated on-farm from non-destructive, plant morphological measurements, using allometric models described by Tittonell et al. (2005a).

2.3. Resource flow maps and partial nutrient balances

Resource flow maps (RFM) were drawn for one case study-farm per farm type in each sub-location (totalling 15 farms) to identify farmers' soil fertility management strategies. Farmers drew schematic maps of their farms with the aid of a facilitator, indicating all production units and the flows of nutrients to and from them, using different colours for inputs (e.g. compost) and outputs (e.g. grains), and symbols for the different production activities. A seasonal time horizon was used, considering the long rains (March to August) of 2002. All nutrient inputs and outputs to and from each production unit within the farm were estimated from the results of the RFM as explained below; nutrient balances at field scale were then calculated as the difference between nutrient inputs and outputs. For conciseness, most of the RFM results and later calculations are illustrated here only for Shinyalu, which represents an intermediate situation with respect to the other localities; this target area has been also often selected as a benchmark for previous research in western Kenya (e.g. De Jager et al., 2001).

Farmers indicated quantities of inputs and outputs to the different production units in local units, such as *goro-goros* (±2 kg of maize), *debes* (±8 kg of maize) or bags (80–90 kg of maize), and these were converted into SI units. Since the specific weight of different materials (grains, tubers, fertilisers, crop residues, etc.) and the actual size of the local units in different farms varied widely, it was necessary to standardise them. A field balance was taken to some of the farms and the weight of one *goro-goro* (the mostly used local unit) of the main crop produce (grains) determined. Many of the values in kg given to local units were taken from previous work in the region, especially for coarse materials like compost or crop residues (Rotich et al., 1999; Van den Bosch et al., 1998). The same applies to the nutrient content of different materials, such as cattle manure, which had been measured for a number of farms of different wealth classes in the region (Rotich et al., 1999; Palm et al., 2001; TSBF, 2001). Crop parameters such as dry matter and nutrient contents, harvest indices and partitioning coefficients were taken from literature (Van Keulen and Wolf, 1986; Marandu et al., 1998; Nzuma and Murwira, 1998; Okalebo et al., 1998; Janssen, 2002) or from own measurements.

Using average values for the dry matter content (DMC, %) of the various crop products, the dry weight (DW_{out}) of each of the outputs from a field (e.g. maize and bean grains, cowpea leaves and Napier grass bundles) was calculated. Since several crops were often grown in each individual field at the same time, the total biomass produced (TB) per field was calculated by first summing the total biomass produced by each crop (dry weight of the output over an average harvest index) and dividing by the field area, according to the following equation:

$$\mathrm{TB}\ [t_{\mathrm{DM}}\ \mathrm{ha}^{-1}] = \sum^{n} \frac{(\mathrm{DW}_{\mathrm{out}}/\mathrm{HI})_i}{\mathrm{Field\ area}} \quad (2.1)$$

where DW_{out} and HI are the dry matter harvested and the harvest index of the 1, 2, …, n crops grown in a certain field. The TB calculated in the described way is useful when flows of C are calculated. Eqs. (2.2) and (2.3) were used to calculate the amount of residues (DW_{res}, t_{DM}) produced by each crop and the total residue yield (TRY, t_{DM} ha^{-1}), respectively.

$$\mathrm{DW}_{\mathrm{res}}\ [t_{\mathrm{DM}}] = \frac{\mathrm{DW}_{\mathrm{out}}/\mathrm{HI}}{\mathrm{DW}_{\mathrm{out}}} - \mathrm{DW}_{\mathrm{out}} \quad (2.2)$$

$$\mathrm{TRY}\ [t_{\mathrm{DM}}\ \mathrm{ha}^{-1}] = \sum_{i=1}^{n} \frac{(\mathrm{DW}_{\mathrm{res}})_i}{\mathrm{Field\ area}} \quad (2.3)$$

Fertiliser use was calculated from the amounts in local units applied to each field and expressed as application rates (kg ha^{-1}), considering the area of each particular field. The nutrient yields in the outputs (NY_{out}, kg ha^{-1}) and in the residues (NY_{res}, kg ha^{-1}) were calculated from the DM yield and average nutrient contents for each crop type. Average carbon content in the biomass dry matter was assumed to be 45% unless

particular information was available. Inputs of nutrients as both organic (NI_{of}, kg ha^{-1}) and mineral fertilisers (NI_{mf}, kg ha^{-1}) were calculated from the application rates (kg ha^{-1}) and the nutrient contents of each fertiliser type.

2.4. Soil data

Topsoil (0–15 cm) samples were taken with an auger at five points per field (average field sizes of ca. 0.2 ha) from all the production units identified in the farms visited for the second interview. The total number of fields per farm varied between farm types and sub-locations (between 4 and 10), as affected by farm size (Tittonell et al., 2005b). A composite sample of approximately 0.75 kg from each field was taken to the laboratory for soil analyses. The topographic slope was measured at three different points in each production unit by means of a clinometer and the average field slope (m 100 m^{-1}) was calculated. Soil samples were air-dried, sieved through 2 mm and stored at room temperature. Samples taken from one case-study farm per farm type in all sub-locations (15 farms in total – ca. one third of all samples) were analysed using standard methods widely used for tropical soils (Anderson and Ingram, 1993). Samples taken from three farms per farm type from all sub-locations (45 farms in total) were analysed by diffuse reflectance spectroscopy, using a FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1 nm using the optical setup described in Shepherd et al. (2003). Their contents of soil C, total N and extractable P were predicted using the spectral library approach described by Shepherd and Walsh (2002). The measured values for the one-third of the samples that was analysed by conventional laboratory methods were calibrated to their reflectance spectra using partial least squares regression implemented in the Unscrambler software (CAMO Inc., Corvallis, OR, USA). The regression models were then used to predict values. The spectral predictions for C, N and available P were moderately accurate: root mean square errors of prediction, based on full hold-out-one cross-validation, were C, 1.6 g kg^{-1}; N, 0.33 g kg^{-1}; and available P, 2.0 mg kg^{-1}.

2.5. Statistical analysis

The statistical significance of the differences between field types and farmers' land quality classes for nutrient status in the soils was assessed by analysis of variance (ANOVA), with Genstat 6, using 'Sub-location' and 'Field type' as factors (three sub-locations, four field types). The C, N and P spectral predictions were also subjected to ANOVA considering the factors 'Sub-location', 'Farm type' and 'Field type' and their interactions (three sub-locations, five farm types, three field types). A separate analysis was performed for the particular 'home garden' (HG) field type, using 'Sub-location', and 'Farm type' as factors (three sub-locations, five farm types).

3. Results

3.1. Categorising and describing field types

Different field types were identified within a farm, varying in production activities, resource allocation and management practices, as revealed by the farm transects (see example in Fig. 1). The home gardens (HG) were the small fields around the homestead, used for a variety of crops sharing small pieces of land or intercropped (see example for Shinyalu in Table 1) which were often absent in the larger farms of Aludeka. The HG were normally managed by women and often the first fields to be planted and weeded, receiving kitchen wastes and the sweepings from the house. The grazing sites (GS) included areas not suitable for crops (e.g. shallow soils), areas within the compound where the house was placed or remote fields where crops were not grown due to risk of theft. The close, mid-distance and remote fields (CF, MF and RF, respectively) were those in which more extensive crops were grown, though the diversity of crop types decreased with increasing distance from the homestead (Table 1). Typically, most inputs were applied (e.g. fertilisers, improved seeds) and the highest yields were attained in the CF. The RF were distant and/or difficult to access, and the crop produce more prone to be stolen, particularly in areas of steep slopes. In this type of field, associated with poor quality land, farmers planted their woodlots or crops that are known to produce under conditions of poor soil fertility, such

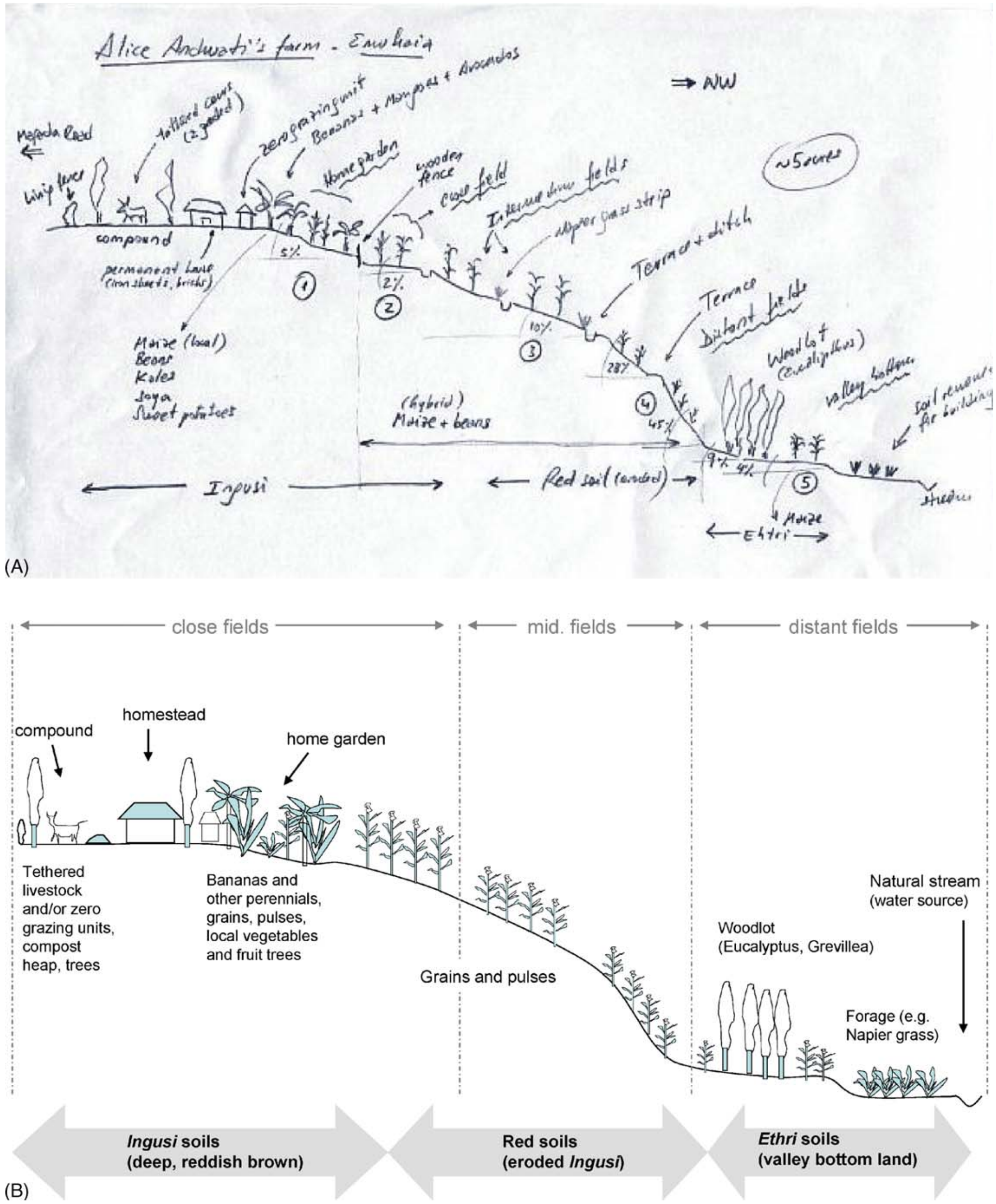

Fig. 1. (A) Example of a farm transect drawn during the first visit to a farm (type 2) in Emuhaia – Western Kenya (scanned from the original field notes). Transects were drawn in collaboration with the farmers or by themselves, while walking the farm and discussing management issues with the aid of a semi-structured checklist. Encircled numbers in the drawing indicate different production units. Horizontal arrows at the bottom indicate dominant soil type (e.g. *Ingusi*, as it is locally known). Approximated farm size: 2.3 ha. (B) Schematic representation of a generic farm in Emuhaia and Shinyalu based on the farm transects. Grains and pulses are normally intercropped. In some cases, the cattle manure is collected in compost pits instead of heaped. In the flatter landscape of Aludeka, however, there was no clear association between farm layout and topography.

Table 1
Average area, distance from the homestead, and most frequently grown crops for the different field types, averaged over all farm types at Shinyalu ($n = 19$ farms)

	Field type			
	Home gardens	Close fields	Mid-distance fields	Remote fields
Average area (ha)	0.07	0.18	0.23	0.23
Average distance (m)[a]	10 ± 3.6	26 ± 8.6	54 ± 17	82 ± 21
Minimum (m)	5	15	36	52
Maximum (m)	19	40	100	120
Most frequently grown crops (frequency %)				
Maize/beans	37	82	73	53
Maize	4	3	4	14
Beans	12	3	4	0
Cowpeas[b]	12	17	8	5
Sweet potatoes	8	0	8	16
Cassava	4	3	0	0
Kales	4	3	0	0
Sugar cane[c]	4	0	0	0
Banana	19	0	0	0
Napier grass	0	3	4	6
Others	8	3	8	5

[a] From the homestead.
[b] Normally intercropped.
[c] Eating type.

as sweet potatoes or Napier grass. In the MF an intermediate management situation was found, strongly affected by the farm type. In wealthy farms they were managed in a similar way to the CF, though input use was less intense.

The field types grouped within ‘special niches’ appeared only in some farms as a result of physical discontinuities or history of use (Table 2), representing small areas of land. The permanent fallow fields (PF) were the most frequent. They were associated with rocky outcrops, steep slopes or *murrams* (i.e. laterite concretions) in Emuhaia and Shinyalu. In Aludeka, due to labour shortage and land availability, poor but potentially cultivable land was left permanently as fallow and/or sporadically used for cattle grazing. The valley bottom fields (VB) were found in Emuhaia and Shinyalu, due to the hilly landscape, and regarded as naturally fertile areas, managed without fertilisers. The swamps (SW) were the preferred niches for cash crops (e.g. cotton, rice, and tobacco) for most farmers in Aludeka due to their dark, fertile soils and were seasonally rented for that purpose. Ex-boma sites (EB) were the places where the homestead had been for some time (about 10–15 years) before moving it to another part within the farm, accumulating fertility from animal droppings and kitchen wastes. They were not found in Emuhaia due to land scarcity, and were only found among the poorest farms in Shinyalu due to the semi-permanent characteristics of their houses (i.e. thatched roofs and mud walls). In Aludeka, where even wealthy families had semi-permanent houses, this type of niche was more common. Due to land availability and to the local grazing system, a higher frequency of the fertile Ex-Kraal (i.e. local term for a small, fenced piece of land used to keep cattle in during the night) sites (EK) was observed in Aludeka, which they rotated after about 4 years.

3.2. Varying productivity and resource allocation within the farm

The dry matter yield of the crops and crop mixtures grown in the different field types within a farm varied widely, as illustrated by the nutrient balances calculated from the results of the resource flow maps drawn in Shinyalu (Fig. 2A). However, differences between farm types for a certain field type were often larger than between the fields of an individual farm; e.g. biomass yields in the close fields of type 2 farms compared with farms of type 5 differed more than between the close and remote fields within each of these farm types. In the wealthier type 2 farms, cash

Table 2
Special niches and their frequency of occurrence at the different sub-locations ($n = 59$ farms)

Sub-location	Special niches (% of farms in which they appear)				
	Valley bottoms	Permanent fallow[a]	Swamps	Ex-*boma*	Ex-*kraal*
Emuhaia	33	33	7	0	0
Shinyalu	40	47	13	13	7
Aludeka	0	33	21	40	20

[a] Waste land.

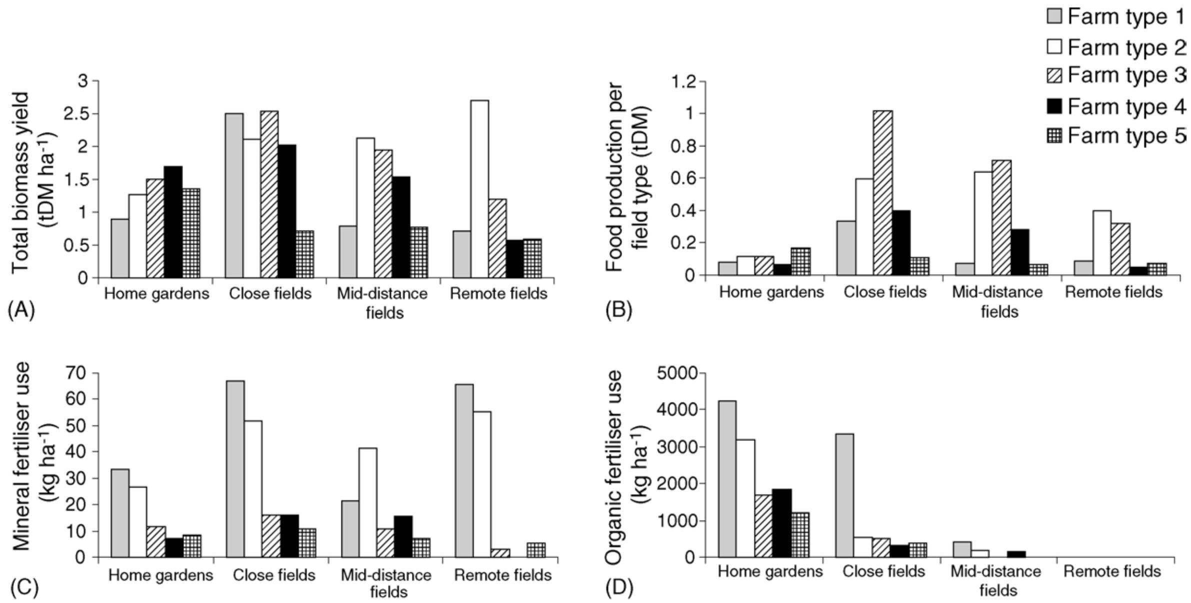

Fig. 2. Outputs and inputs of nutrients from and to the different fields of the case study farm types 1–5 at Shinyalu, western Kenya. Estimations from the results of the resource-flow maps. *Outputs*: dry matter yield of the outputs from each field (A) and total food production per field (B). Outputs included all biomass harvested/removed from a certain field, including for instance Napier grass or Tea, whereas 'food' production from a field included only the edible produce, such as grains or vegetable leaves. *Inputs*: mineral (C) and organic (D) fertilisers use in the different fields of the case study farms. All types of mineral fertilisers and organic resources used as soil amendments were included.

crops like tea or perennial crops like fodder grasses were normally grown on the steep slopes subject to erosion, thus producing good biomass yields in remote fields. In general, most of the farm produce was obtained from the close and mid-distance fields (Fig. 2B). While the mid-distance fields sustained mainly maize/beans intercrops, crops produced in the close fields were normally those of the highest value, like kale and cabbage.

Mineral fertilisers were used with varying intensities in the different field types (Fig. 2C). The wealthiest farm types 1 and 2 applied them in all field types, and relatively high rates were used in the remote fields of these case study farms. For the other farm types little fertiliser was used in the remote fields and almost all application rates were less than 20 kg ha^{-1}. The use of organic fertilisers (Fig. 2D) decreased strongly with the distance from the homestead and/or grazing sites, and differed between the crops. Vegetable crops grown in the home gardens received most of the organic resources, followed by the cash and grain crops grown in the close and mid-distance fields. Virtually no organic resources were applied to the remote fields, due to the extra effort required to transport coarse materials to distant parts of the farm.

Crop residues were used as fodder, burnt, composted or incorporated in situ. Residues used as fodder were transported to grazing sites and fed to animals. Crop residues were burnt as fuel for cooking, to clear the fields before planting and, in the case of bean residues, to produce salt. In Emuhaia and to a lesser extent in Shinyalu, crop residues were taken from the field to a compost pile or compost pit, mixed with animal manure, ashes and kitchen wastes and used as organic fertilisers in planting holes. Residues were most commonly incorporated in Aludeka. In Emuhaia and Shinyalu residues were only incorporated in the home gardens and close fields.

3.3. Soil fertility status

Soil texture and organic C varied significantly ($P < 0.01$) between sub-locations, but did not appear to be good indicators for differences in soil fertility between field types (Table 3). Total soil N was on average very poor in Aludeka (0.5 g kg^{-1}), low in

Table 3
Inherent and actual soil fertility indicators for different field types in the three sub-locations ($n = 141$[a])

Sub-location	Field type	Clay + silt (%)	SOC (g kg^{-1})	Total N (g kg^{-1})	pH in water (1:2.5)	Extracted P (mg kg^{-1})	Exchangeable cations (cmol$_{(+)}$ kg^{-1})			
							K^+	Ca^{2+}	Mg^{2+}	H^+
Emuhaia	HG	53.1	12.9	1.3	6.1	19.8	0.54	5.5	1.7	0.13
	GS	49.7	12.1	1.5	6.1	1.9	1.16	3.1	1.7	0.22
	CF	50.9	11.7	1.1	5.6	3.5	0.31	4.2	1.4	0.42
	MF	51.1	12.1	1.2	5.3	2.0	0.22	3.6	1.3	0.39
	RF	49.8	10.5	1.0	5.1	2.1	0.14	2.6	1.1	0.55
Shinyalu	HG	76.4	18.1	1.2	5.7	14.0	0.53	8.0	2.7	0.49
	GS	77.5	18.5	1.6	5.3	1.6	0.37	6.0	2.5	0.37
	CF	78.8	18.1	1.9	5.3	6.6	0.32	6.4	2.1	0.29
	MF	78.3	17.3	1.6	5.3	4.0	0.35	6.5	2.0	0.39
	RF	76.2	17.2	1.3	5.2	2.7	0.28	6.1	2.6	0.44
Aludeka	HG	36.1	6.9	0.3	5.4	2.5	0.28	2.4	0.7	0.18
	GS	36.1	7.5	0.5	5.6	5.3	0.57	2.1	0.7	0.45
	CF	42.9	8.8	0.6	5.8	5.6	0.44	3.9	0.8	0.25
	MF	44.3	8.6	0.6	5.4	2.9	0.25	2.9	0.9	0.26
	RF	39.4	7.9	0.5	5.2	2.3	0.15	2.3	0.7	0.28
Site × field type (*P*-value)		0.484	0.302	0.07	0.06	0.720	0.01	0.229	0.396	0.445
S.E.D. (general)		3.36	1.03	0.2	0.24	7.1	0.15	0.8	0.4	0.18
S.E.D. (field types)		1.95	0.60	0.1	0.14	4.1	0.09	0.5	0.2	0.11
S.E.D. (sites)		1.46	0.45	0.1	0.10	3.1	0.07	0.3	0.2	0.07

[a] Fields classified as special niches were not included in this analysis because they were not present in all farms.

Emuhaia (1.2 g kg^{-1}) and on the lower limit of the regional range of sufficiency indicated for maize crops (ca. 1.5 g kg^{-1}, FURP, 1994) in Shinyalu. The average C:N ratio was the highest in Aludeka (ca. 15) and the lowest in Emuhaia (ca. 10). In all sub-locations the grazing sites had total N contents that were the same or higher than the site average. Net concentration of nutrients occurred where cattle were tethered and fed, and because these fields are normally not tilled. This effect was less evident in Aludeka due to the availability of rangeland. Distance from the homestead and accessibility helped to explain the distribution of total soil N within the farm in Shinyalu, where the topography was steeper. A significant ($P < 0.05$) decrease in topsoil pH was observed from the close towards the remote fields in Emuhaia and Aludeka, whereas in Shinyalu only the home gardens had significantly higher pH.

In general, extractable P decreased from the close towards the remote fields although in all cases it was very to extremely low (Table 3). Exchangeable K did not differ significantly ($P < 0.05$) between sub-locations but varied across field types, describing a negative gradient from the home gardens towards the remote fields in most cases. Both exchangeable Ca and Mg differed significantly between sub-locations although only the former varied across field types.

An analysis of variance was performed using spectral predictions of soil C, total N and extractable P (Fig. 3). These results largely confirmed the results of chemical analysis. The average predictions of soil organic C and total N were not widely different between field types or farm types. The effect of Field type and its interaction with the Sub-location were significant for both C and N predictions, and no significant interactions between Farm type and Field type were observed. For the extractable P predictions the effect of sub-location, farm type and field type were highly significant ($P < 0.001$) and a significant ($P < 0.05$) interaction Sub-location by Farm type was also observed. A separate analysis conducted for the home gardens of those farms (Table 4) showed significant Sub-location effects for C and N predictions ($P < 0.01$), farm type effects for C and P ($P < 0.05$) and no significant Sub-location by Farm

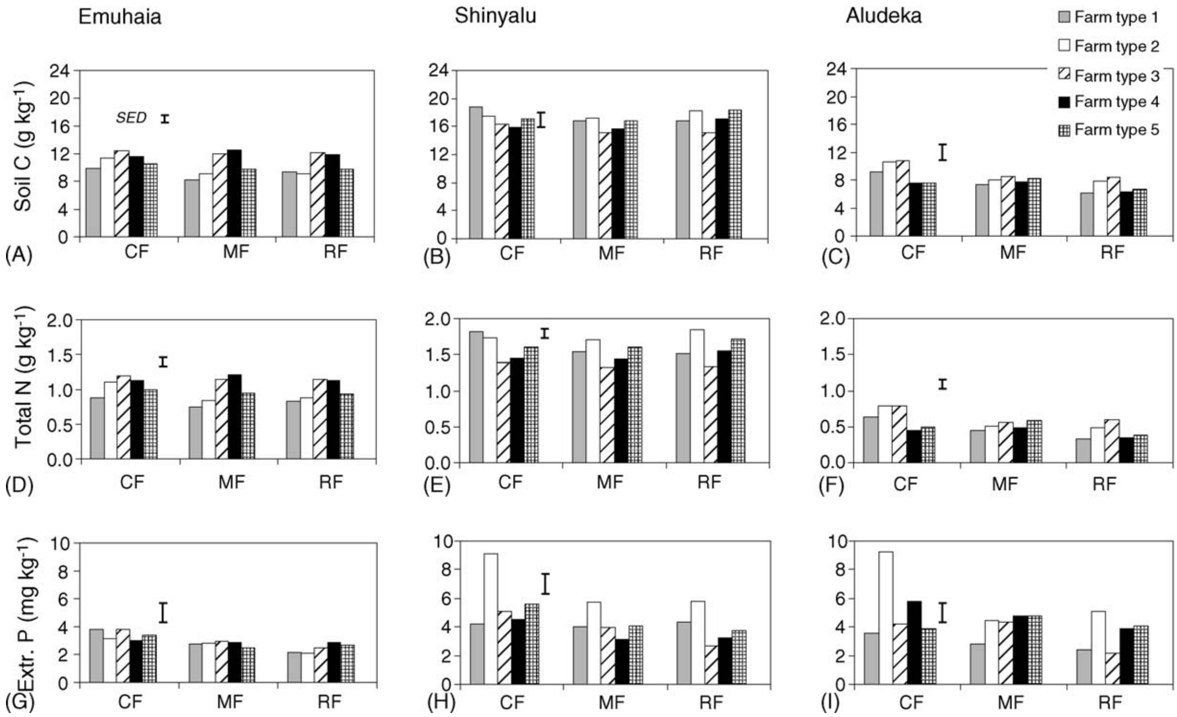

Fig. 3. Predicted values for soil C, total N and extractable P by diffuse reflectance spectroscopy of topsoil (0–15 cm) samples from Emuhaia (A, D and G), Shinyalu (B, E and H) and Aludeka (C, F and I) sub-locations in western Kenya. Samples were taken on 45 farms from close, mid-distance and remote (CF, MF, RF, respectively) fields with respect to the homestead. Farms were classified according to a typology (farm types 1–5) that considered resource endowment, household objectives and sources of farm income. Vertical bars represent the standard error of the differences (S.E.D.).

type interactions. The home gardens of the farms of type 2 had higher predicted C, N and P values, followed by farms of types 3 and 1.

3.4. Resource flows, nutrient balances and stocks

The relatively narrow differences observed between field types for the various soil fertility indicators in Table 3 suggest that the assessment of soil fertility gradients should focus on each particular farm, rather than taking averages for the different field types across farms, to properly capture the within-farm variability. To illustrate this point, Fig. 4 shows a schematic representation of a case study farm in Shinyalu (farm type 3) and the resource flow map drawn in that particular farm. The scheme indicates the variation in soil N for the different field types, ranging from 2.6 g kg^{-1} in one of the close fields (the smallest one) to 0.5 g kg^{-1} in the remote fields; a much wider difference than for the site averages (cf. Table 3) – and striking for two fields that are only at about 100 m away from each other. The N content for most of the land in this farm was below the average value for Shinyalu (1.5 g kg^{-1}).

As a consequence of the management patterns identified in the case-study farms, input rates of C and N were much higher in the home gardens and in the close fields than in the other field types (Fig. 5A and B). The pattern of N allocation from the home gardens to the remote fields was mostly explained by the pattern of organic resource allocation (cf. Fig. 2D). The distribution of mineral fertiliser N was mainly affected by farm type (Fig. 5C). Instead, the distribution of N added through organic inputs was chiefly affected by field type (Fig. 5D), reflecting the distance from the homestead.

The partial C balances were negative for most fields of all the case-study farms, illustrating that the amount

Table 4
Soil C, total N and extractable P predictions obtained by diffuse reflectance spectroscopy of topsoil (0–15 cm) samples taken from the home gardens of three farms per farm type per sub-location ($n = 45$ farms)

Sub-location	Farm type	Prediction		
		Soil organic C (g kg^{-1})	Total soil N (g kg^{-1})	Extractable P (mg kg^{-1})
Emuhaia	1	10.7	1.0	3.9
	2	14.3	1.4	6.8
	3	13.3	1.2	5.4
	4	13.3	1.3	2.8
	5	12.3	1.2	2.4
Shinyalu	1	16.1	1.4	3.6
	2	19.6	1.8	5.3
	3	16.4	1.4	5.7
	4	15.5	1.4	3.5
	5	16.3	1.6	4.7
Aludeka	1	9.9	0.8	3.4
	2	10.6	0.8	4.0
	3	9.0	0.6	3.1
	4	7.4	0.4	3.7
	5	6.0	0.3	3.5
S.E.D.				
Sub-location (A)		0.8	0.1	0.5
Farm type (B)		1.0	0.1	0.6
A × B		1.8	0.2	1.1

S.E.D.: standard error of the differences.

of C incorporated by crop residues and organic fertilisers was obviously less than the amount of C harvested with the biomass removed (Fig. 5E). In the home gardens, however, a net C input was observed due to the transfer of biomass from other fields via crop residues or compost (these *partial* balances do not consider e.g. C fixation by weeds, or soil C lost by erosion). The partial N balance was negative in most fields of all case-study farms (Fig. 5F). Only in the home gardens of the wealthiest type 1 and type 2 farms was the partial N balance positive. The N balance tended to be more negative in those fields where the highest yields were attained, especially in the poorer farms (cf. Fig. 2A and B). Even when fertilisers were applied, the application rates were insufficient to compensate crop removal in most cases (Fig. 2C and D).

The P concentrations in the home gardens of Emuhaia and Shinyalu reflected the inputs of ash, composted crop residues and manure, together with kitchen wastes and house sweepings normally containing chicken dung (cf. Tables 3 and 4). In Aludeka, the home gardens were not managed in this way, nutrient-demanding crops produced on inherent soil fertility are seasonally moved from one spot to another within the farm. In all sub-locations, the close fields often received P-containing fertilisers, particularly di-ammonium phosphate (18:46:0). However, the small soil P concentrations shown for these fields in Table 3 reflect the small application rates of fertiliser used by the farmers and the P-fixing capacity of these soils. The high pH and exchangeable cations confirmed the effects of ash inputs to the home gardens.

3.5. Farmers' perceptions of soil fertility gradients

Independent of the field typology proposed to categorise within-farm variability (field types – cf. Tables 1 and 2), farmers classified their fields into fertile, average and poor fields, though the reasons behind this classification varied widely between sub-locations as well as among farmers, and were not only related to nutrient availability (Table 5). Soil erosion, followed by soil depletion and input use were the main reasons given by farmers to explain differences in crop

Table 5
Farmers' criteria for land quality classification and reasons behind yield variability ($n = 45$ farms); relative frequencies represent the number of farmers giving a certain reason/answer over the total number of farmers (they often gave more than one reason)

	Relative frequency %		
	Emuhaia	Shinyalu	Aludeka
Criteria for land quality classification			
Soil type[a]	40	33	67
Texture	20	7	53
Water holding capacity	20	7	27
Fertility	13	40	33
Slope	53	73	0
Weed type	27	0	0
Distance from homestead	0	7	20
Others	0	7	7
Reasons for differences in yields among fields			
Water logging	0	0	7
Erosion	73	93	13
Declining soil fertility	60	40	27
Weeds, pests or diseases	47	7	0
Management inputs	40	20	13
Use of different varieties	27	47	0

[a] Often soil type was indicated as the main reason (e.g. red vs. brown soils), and no further specifications were given.

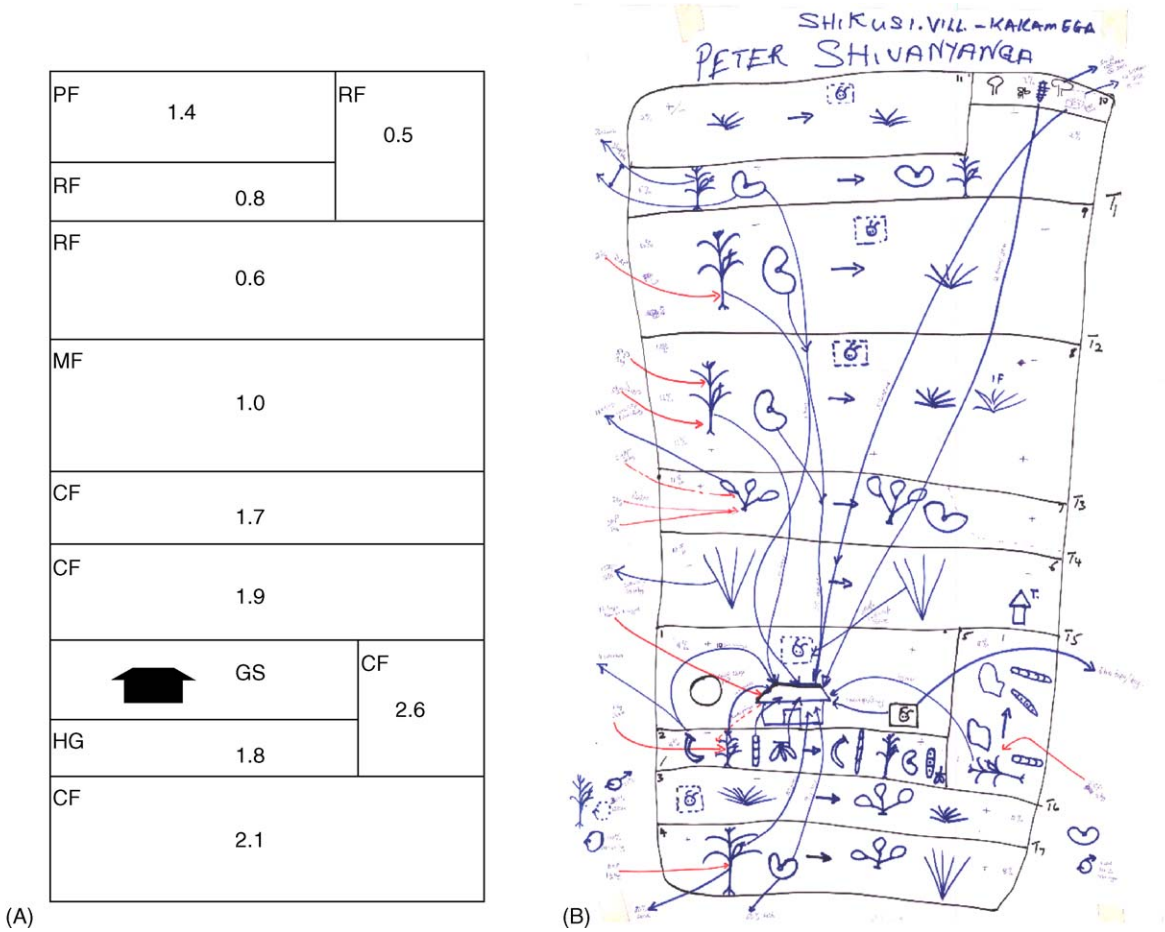

Fig. 4. (A) Schematic representation of a case study farm at Shikusi village, Shinyalu, and (B) the resource flow map drawn by the farmer. The figures in the scheme indicate the average total N content (g kg^{-1}) in the topsoil of the main identifiable production units. Fields were categorised according to the proposed typology: HG: home garden; GS: grazing site; CF, MF and RF: close, mid-distance and remote crop fields, respectively, and PF: permanent fallow field or wasteland. The scheme followed the dimensions of the drawing; the scale and actual proportions were not respected. Approximated farm size: 2.1 ha.

yields between fields in Emuhaia and Shinyalu, whereas soil texture and the inherent fertility of soils were the main ones in Aludeka. Cross-checking the initial categorisation of field types with those of the farmers revealed that in most cases the home gardens and the close fields were classified as ‘fertile’ in all sub-locations, whereas the remote fields fell mostly in the ‘poor’ class (Table 6). For the mid-distance fields the results were more variable and no clear trend was observed across localities.

Some soil and landscape properties tended to vary between land quality classes as distinguished by farmers in all sub-locations (Fig. 6A–F). The topographic slope of the fields varied between land classes in Shinyalu and secondarily in Emuhaia, but not in the flatter landscape of Aludeka. No differences in texture were observed between land quality classes in any of the sub-locations; again, such differences were more evident within each individual farm. Soil C tended to decrease from ‘fertile’ to ‘poor’ fields in Emuhaia and Aludeka, though the observed differences of 20–30% were not statistically significant ($P < 0.05$); such a variation was not observed for the finer soils of Shinyalu. Total N did not differ significantly ($P < 0.05$) whereas extractable P and exchangeable K showed highly significant ($P < 0.01$

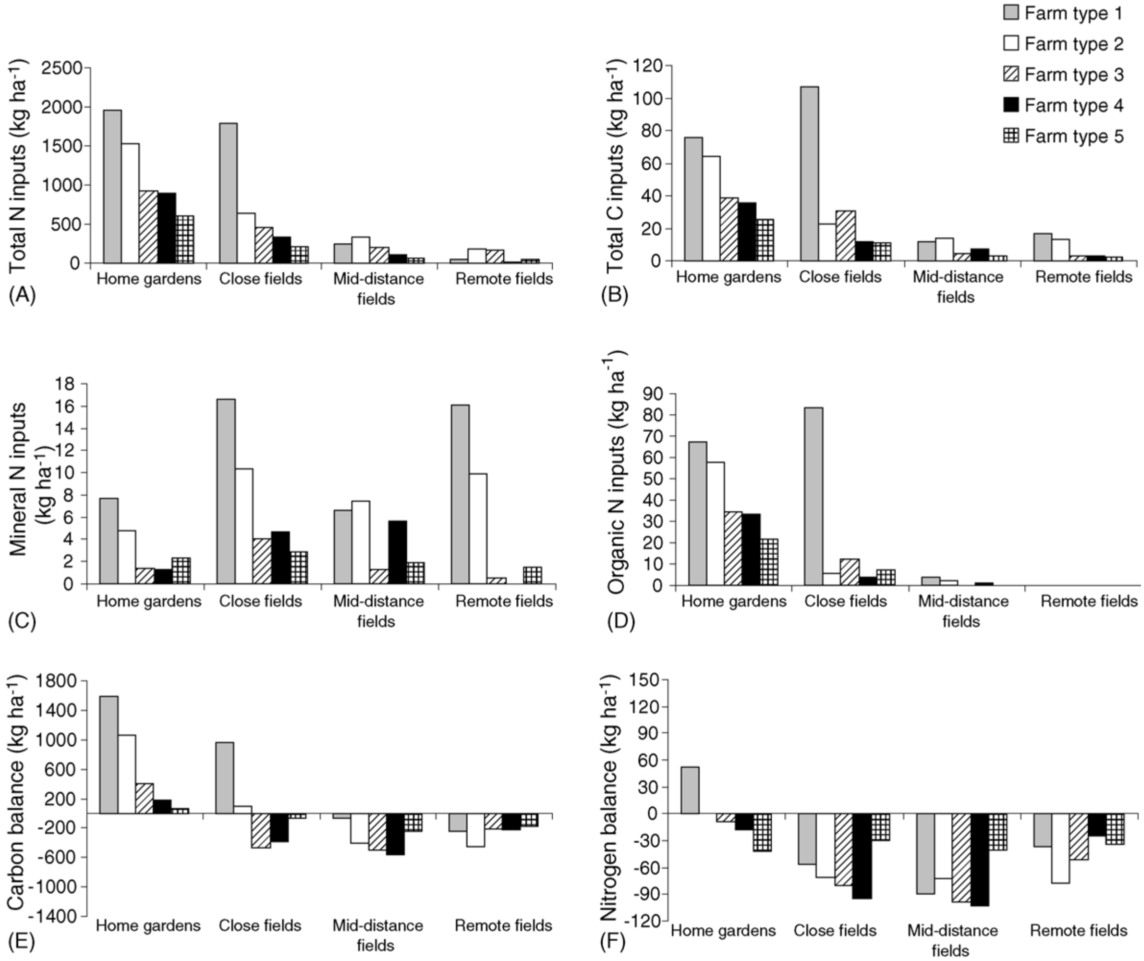

Fig. 5. Total C (A) and N (B) inputs; N inputs applied as mineral (C) and organic (D) fertilisers; partial C (E) and N (F) balances for the different field types of the case study farm types 1–5 at Shinyalu, western Kenya. Estimations considering organic and mineral fertilisers, residue management and harvests from each field type according to the results of the resource-flow maps. The estimations of total N inputs (B) used to calculate N balances (F) included mineral and organic fertilisers (C and D), plus N in crop residues (when they were incorporated) and in other organic sources (e.g. kitchen wastes). Note the important differences in the scales of the *y*-axes.

and $P < 0.001$, respectively) differences between land quality classes in all sub-locations (Fig. 6D–F). Fields classified as 'fertile' had much more extractable P than the 'average' and 'poor' across localities, though all samples fell below the critical value of 15 mg kg^{-1}.

The land quality classes distinguished by farmers differed also in productivity and crop management. Not surprisingly, maize yields estimated on-farm varied between land quality classes in all sub-locations, and were significantly ($P < 0.05$) larger in the 'fertile' fields (Table 7). Besides differences in soil fertility presented above (cf. Fig. 6), the intensity and timing of crop management practices also varied widely between farmers' land classes. Fertile fields tended to be planted earlier, closer to the optimum date at each sub-location, using denser plant populations and were weeded more keenly, having low (score 1) weed and particularly *Striga* infestations. *Striga* problems were more intense in Emuhaia and absent in Shinyalu. The delay in planting date (relative to the local optimum) tended to be the longest in the poor and often furthest fields of Aludeka, where land sizes were largest. The relative distance from the homestead (RDH, which relates distance to farm size) increased

Table 6
Crosschecking the field typology initially adopted (home gardens, close to remote fields) with the classification of land qualities (fertile to poor) done by farmers independently, at the three sub-locations ($n = 45$ farms)

Sub-location	Land quality class	Field types (frequency in each quality class %)			
		Home garden	Close fields	Mid-distance fields	Remote fields
Emuhaia	Fertile	76	52	39	19
	Average	14	29	36	25
	Poor	10	19	25	56
Shinyalu	Fertile	62	75	5	7
	Average	31	17	53	36
	Poor	8	8	42	57
Aludeka	Fertile	62	67	29	13
	Average	23	27	42	9
	Poor	15	7	29	78

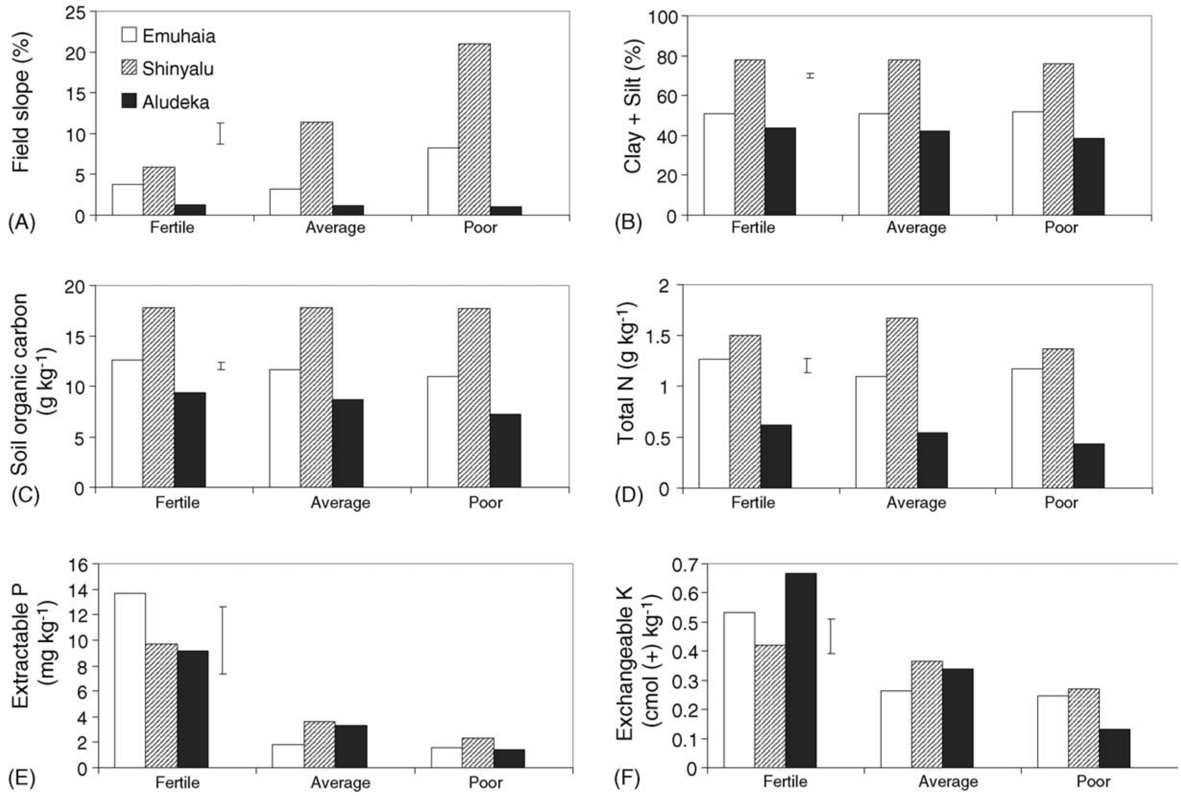

Fig. 6. Soil and landscape properties of the production units that were classified by farmers according to land quality in three sub-locations of western Kenya. (A) Topographic field slope; (B) soil clay plus silt fraction; (C) soil organic carbon; (D) total soil nitrogen; (E) extractable P; (F) exchangeable K. Sample sizes: 53 (Aludeka), 55 (Emuhaia), 53 (Shinyalu). Vertical bars represent the standard error of the differences (S.E.D.).

Table 7
Maize yield estimates[a], average values of the variables grouped as crop management factors and relative distance from the homestead for the different land quality classes as recognised by farmers across sub-locations ($n = 184$)

Sub-location	Land quality class	Maize yield (t ha^{-1})	Crop management factors				RDH
			DPD (days)	PP (pl m^{-2})	Weed score	Striga score	
Emuhaia	Fertile	2.4	17.9	2.43	0.70	0.26	0.32
	Average	1.8	18.6	2.40	1.19	0.76	0.47
	Poor	0.9	27.3	2.16	1.65	1.24	0.60
Shinyalu	Fertile	2.5	15.6	2.62	0.85	0	0.23
	Average	1.5	16.9	2.09	1.45	0	0.53
	Poor	1.0	22.1	1.93	1.69	0	0.69
Aludeka	Fertile	1.5	18.0	1.73	0.91	0.14	0.28
	Average	1.1	21.6	1.76	1.38	0.19	0.40
	Poor	0.5	33.6	1.57	1.72	0.67	0.56
Sub-location × land quality (*P*-value)		ns	ns	0.06	ns	0.02	ns
S.E.D. (general)		0.2	4.9	0.16	0.28	0.20	0.06
S.E.D. (land quality)		0.1	3.1	0.09	0.16	0.12	0.04
S.E.D. (sites)		0.1	3.1	0.09	0.16	0.12	0.04

DPD: delay in planting date; PP: plant population density; weed and striga scores: 0 = absent, 1 = low, 2 = medium, 3 = high; RDH: relative distance from the homestead; S.E.D.: standard error of the differences; ns: non significant at $P < 0.1$.

[a] Yield estimations were performed with allometric models developed for local maize genotypes (Tittonell et al., 2005a), using plant morphological measurements.

from the 'fertile' to the 'poor' land units on average, confirming the agreement between both field typologies shown in Table 6.

4. Discussion

Varying spatial patterns of resource allocation were identified within the farms – largely affected by their characteristic production strategies, resource endowment and factor constraints (i.e. farm type). As a consequence, strong variation in soil fertility status between fields was observed when each individual case-study farm was considered separately (cf. Fig. 4). However, the differences in the average soil fertility status between field types (Tables 3 and 4, Fig. 3) were often not as striking as those observed in previous studies (e.g. Prudencio, 1993; Tiessen et al., 2000). This was probably also due to the general alarming degree of soil depletion in western Kenya (Soule and Shepherd, 2000). Most samples had values for the different soil fertility indicators that were below published critical limits (e.g. Cochrane et al., 1985; Landon, 1991), except for those taken in the small fields around the homestead.

The partial nutrient balances at field scale revealed the existence of C and N 'accumulation' areas within the farm. In agreement with earlier observations (Mapfumo and Giller, 2001), the areas being depleted were much larger than the areas of 'accumulation', leading to an overall negative nutrient balance at farm scale. Household wastes and crop residues from other fields were brought to the home gardens and grazing sites in the form of compost or animal feeds, respectively. Besides, nutrients accumulated in the home gardens would not be efficiently used by grain and pulse crops often sparsely planted and shaded by banana plants and trees, affecting the magnitude of nutrient outflows as harvested crop parts. This resource flow pattern, however, was not always clearly reflected by the results of the soil analysis (cf. Table 3). As reported elsewhere (e.g. De Jager et al., 2001), nutrient balances helped to identify trends of nutrient depletion and accumulation but these can only be interpreted in relation to nutrient stocks (Smaling et al., 1997).

Fields within a farm were classified according to their relative position with respect to the homestead, to the type of crop grown and to general management and resource use intensity. As previously suggested

(Brouwer et al., 1993; Carter and Murwira, 1995), the distance from the homestead tended to affect the allocation of production activities and resources (Table 1, Figs. 2, 4 and 5). Even in farms with land areas as small as 0.45 ha, gradients existed where productivity declined with increasing distances from the homestead. Fields that were ‘distant’ from the homestead, or more difficult to access due to steep slopes were managed as remote fields, although they were not at such large distances as the ‘bush fields’ which exist in other Africa farming systems (Morgan, 1969). However, when sufficient labour was available and/or when no association existed between farm layout and land quality, the distance from the homestead did not provide a clear differentiation between fields in terms of management. Therefore, the management of close and remote fields was strongly affected by the farm size, resource endowment and labour availability (i.e. field type x farm type interaction) and secondarily by the soilscape variability (sub-location effect).

In literature on soil fertility management in African farming systems the concept of ‘niches of soil fertility’ is often found (e.g. Mango, 1999, Crowley and Carter, 2000), and several attempts to improve the efficiency of nutrient flows targeted those niches for technology development. However, these should be seen as conceptual rather than physical niches, as the fields termed as special niches in this study (cf. Table 2) were restricted in area and not broadly distributed among the farms visited. They represented a limited contribution to the overall farm productivity, and targeting them when designing soil fertility management strategies will not benefit a large number of farmers in western Kenya.

The land quality classification by farmers produced a reasonable discrimination of soil fertility situations within the farm (cf. Fig. 6). Both inherent land quality and land-use history were used as classification criteria (cf. Table 5), whereas soil fertility was not explicitly mentioned as one of the causes for yield variability. Although farmers classified their own fields without comparing them with fields of other farmers, their classification was strongly linked to resource allocation patterns, in agreement with previous experience (Ramisch, 2004; Defoer et al., 2000). Since what drives farmers’ decisions is what *they* perceive as good or poor quality land, management intensity gradients were clearly identified alongside the gradients of soil fertility.

The allocation of production activities to the various fields within the farm, their level of production, and the amount and quality of nutrient resources applied to them varied also between farmers of different social classes (Figs. 2 and 5). The case-study farms selected on the basis of the farm typology (Tittonell et al., 2005b) allowed study of the effect of management practices and decisions, and yielded distinguishable resource flow patterns (Figs. 2 and 5). However, the average soil C, total N and extractable P contents predicted by diffuse reflectance spectroscopy (Fig. 3) did not show clear differences between farm types. Instead, there were strong sub-location by farm type interactions for C and N, suggesting that differences do not vary consistently with the farm stratification across sub-locations.

Most farmers in Emuhaia and Shinyalu used mineral fertilisers, in agreement with other studies in the region (Kenya Ministry of Agriculture and Rural Development, 2001; Braun et al., 1997). However, the application rates were extremely low and the nutrient balances were negative in most fields, irrespective of the farm typology. As observed for several African farming systems (e.g. Dembélé et al., 2000; Rotich et al., 1999), the magnitude of the C and N balances for a given field type tended to vary between farm types (cf. Fig. 5). However, in our study important differences were only observed for the more intensively managed home gardens, and to some extent for the close fields. Wealthier farmers were able to use mineral fertilisers even in their farthest fields, whereas organic resources were mainly used near the homestead in all farm types. Labour availability and the capacity to invest in nutrient inputs determined different rates of nutrient depletion for the different farm types.

In a densely populated locality such as Emuhaia, the magnitude of within-farm soil fertility gradients tended to be smaller than in the other sites (e.g. see ranges in soil C in Tittonell et al., 2005b). The land was subdivided to such an extent that it tended to be homogenous in terms of its inherent biophysical properties, and farming has become a secondary activity for many farmers (ca. 80% of farmers had a source of off-farm income in Emuhaia), in agreement with previous observations (Crowley and Carter,

2000). Additionally, the existence of a market for fresh produce (e.g. milk and vegetables in densely populated areas) determined to a larger extent the decisions on land use and resource allocation to different activities. In the relatively distant and sparsely populated areas such as Aludeka, or where variability in land qualities originates from topography as in Shinyalu, different *soilscape* units could be identified within a single farm (cf. Tittonell et al., 2005b). As in other smallholder systems of East Africa (e.g. Baijukya et al., 2005), farmers identified and managed these different land qualities allocating activities and resources according to their production potential, and constrained by socio-economic factors.

5. Conclusions

The integrated methodological approach followed in this work helped increasing the understanding of the management aspects of the household that affect the origin and magnitude of the soil fertility gradients. By considering farmers' perceptions in the characterisation of within-farm variability, it was possible to identify resource allocation patterns in relation to soil fertility gradients. Such an approach could also be considered while targeting soil fertility management strategies and fine-tuning decision aids for resource allocation in smallholder farms.

Farmers manage their fields according to their perceived quality, so that the soil fertility gradients are in fact also management intensity gradients. Additionally, the heterogeneity in agricultural productivity, in terms of the intensity of nutrient depletion, and the allocation of resources and production activities to the different fields within the farm varied in magnitude between farm types and across localities. In areas of high population density (such as Emuhaia), the intensity of input use, the proximity to factor markets and the access to off-farm income appear to override the inherent biophysical properties in determining the pattern of resource allocation and the magnitude of the soil fertility gradients within a farm. Conversely, in areas of sparse population density and/or high variability in the inherent biophysical background, perceived land quality determines the resource allocation pattern emerging from farmers' management decisions. Since scarce resources and investments are preferably allocated to less risky land units, such a pattern results in increased within-farm soil fertility gradients.

Management decisions at farm scale, which are affected by both biophysical and socio-economic factors, have an important impact on the resulting soil fertility. To understand opportunities for sustainable intensification, an approach is needed to analyse the combined effect of management and current soil fertility on farm productivity, raising the scale of analysis to the livelihood level. Some operational decisions are often made on a day-by-day basis, contrasting with the strategic questions on sustainability of the farming systems in view of long-term changes of biophysical and socio-economic conditions. Thus, there is a clear need to include the dynamics of the farming systems in the analysis of tradeoffs between factors affecting soil fertility management at multiple spatio-temporal scales.

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References

Anderson, J.M., Ingram, J.S.I., 1993. Tropical Soil Biology and Fertility. A Handbook of Methods. CAB International, Wallingford, UK, p. 221.

Barrios, E., Bekunda, M., Delve, R.J., Esilaba, A., Mowo, J., 2001. Identifying and classifying local indicators of soil quality. In: Eastern Africa Version. Participatory Methods for Decision Making in Natural Resource Managementunknown:book, CIAT-SWNM-TSBF-AHI, Nairobi, Kenya.

Baijukya, F.P., de Ridder, N., Masuki, K.F., Giller, K.E., 2005. Dynamics of banana-based farming systems in Bukoba District, Tanzania: changes in land use, cropping and cattle keeping. Agric. Ecosyst. Environ. 106, 395–406.

Braun, A.R., Smaling, E.M.A., Muchugu, E.I., Shepherd, K.D., Corbett, J.D., 1997. Maintenance and improvement of soil productivity in the highlands of Ethiopia, Kenya, Madagascar and Uganda: an inventory of spatial and non-spatial survey and research data on natural resources and land productivity (African Highlands Initiative Technical Report Series No. 6). International Centre for Research in Agroforestry, Nairobi, Kenya.

Brouwer, J., Fusell, L.K., Herrmann, L., 1993. Soil and crop growth micro-variability in the West African semi-arid tropics: a possible risk-reducing factor for subsistence farmers. Agric. Ecosyst. Environ. 45, 229–238.

Carter, S., Murwira, H., 1995. Spatial variability in soil fertility management and crop response in Mutoko Communal Area, Zimbabwe. Ambio 24, 77–84.

Chikuvire, J., 1998. Socio-economic factors influencing farmers' access to soil fertility resource and management of niches. In: Carter, S., Riley, J. (Eds.), Biological Management of Soil Fertility in Small-scale Farming Systems in Tropical Africa. Final Report of the European union (EU) Project number TS3-CT94-0337. Tropical Soil Biology and Fertility Programme, Nairobi, Kenya, pp. 41–57.

Cochrane, T.T., Sanchez, L.G., Azevedo, L.G., Porras, J.A., Garver, C.L., 1985. Land in tropical America, vol. 3. CIAT, Cali, Columbia.

Crowley, E.L., Carter, S.E., 2000. Agrarian change and the changing relationships between toil and soil in Maragoli, western Kenya (1900–1994). Hum. Ecol. 28 (3), 383–414.

De Jager, A., Onduru, D., Van Wijk, M.S., Vlaming, J., Gachini, G.N., 2001. Assesing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. Agric. Syst. 69, 99–118.

Defoer, T., Budelman, A., Toulmin, C., Carter, S.E., 2000. Building common knowledge. Participatory learning and action research. Part I. In: Defoer, T., Budelman, A. (Eds.), Managing Soil Fertility in the Tropics. A Resource Guide for Participatory Learning and Action Research. Royal Tropical Institute (KIT), Amsterdam.

Dembélé, I., Koné, D., Soumaré, A., Coulibaly, D., Koné, Y., Ly, B., Kater, L., 2000. Fallows and field systems in Mali. In: Hilhorst, T., Muchena, F. (Eds.), Nutrients on the Move: Soil Fertility Dynamics in African Farming Systems. IIED, London, pp. 83–102.

FURP, 1994. Final Report of the Fertiliser Use Recommendation Program (FURP) Volumes V and VII Busia and Kakamega districts. National Agricultural Research Laboratory, Kenya Ministry of Agriculture and Livestock, Nairobi, Kenya.

Giller, K., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building soil nitrogen capital in Africa. In: Buresh, R.J., Sanchez, P.A. (Eds.), Replenishing Soil Fertility in Africa. ASSA, CSSA, SSSA, Wisconsin, pp. 151–192.

Giller, K.E., Rowe, E., de Ridder, N., van Keulen, H., 2005. Resource use dynamics and interactions in the tropics: scaling up in space in time. Agric. Syst., in press.

Janssen, B., 2002. Organic matter and soil fertility. Department of Environmental Sciences, sub-Department of Soil Quality. CM no. 06172101. Wageningen Agricultural University, Wageningen, The Netherlands, 237 pp.

Kenya Ministry of Agriculture and Rural Development, 2001. Annual Reports for Vihiga, Kakamega and Teso districts: Surveys on Population and Agricultural Production.

Landon, R. (Ed.), 1991. Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Booker Tate, Longman Scientific & Technical, Harlow, UK.

Mango, N.A.R. 1999. Integrated soil fertility management in Siaya district, Kenya. Managing African soils no. 7, 28 pp.

Mapfumo, P., Giller, K.E., 2001. Soil fertility management strategies and practices by smallholder farmers in semi-arid areas of Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), PO Box 776, Bulawayo, Zimbabwe.

Marandu, A.E., Ikerra, S.T., Kalumana, M.C., Assenga, R.H., Mutuo, P.K., 1998. Nitrogen mineralisation of organic materials of different quality in a rhodic ferralsol. The biology and fertility of tropical soils. Tropical Soil Biology and Fertility Program (TSBF) Report 1997–1998. TSBF, UNESCO, Nairobi, Kenya, 95 pp.

Morgan, W.B., 1969. The zoning around rural settlements in Tropical Africa. In: Thomas, M.F., Whittington, G.W. (Eds.), Environment and Land Use in Africa. Methuen, London, pp. 301–319.

Nzuma, J.K., Murwira, H.K, 1998. Effect of management on changes in manure nitrogen during storage. The biology and fertility of tropical soils. Tropical soil biology and fertility program (TSBF) report 1997–1998. TSBF, UNESCO, Nairobi, Kenya, 95 pp.

Okalebo, J.R., Muasya, R., Owuor, J., 1998. Effect of fortification of crop residues with urea on maize yield in Uasin Gishu district, Kenya. The biology and fertility of tropical soils. Tropical soil biology and fertility program (TSBF) report 1997–1998. TSBF, UNESCO, Nairobi, Kenya, 95 pp.

Palm, C.A., Ganchego, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric. Ecosyst. Environ. 83, 27–42.

Prudencio, C.F., 1993. Ring management of soils and crops in the West Africa semi-arid tropics: the case of the Mossi farming system in Burkina Faso. Agric. Ecosyst. Environ. 47, 237–264.

Ramisch, J.J., 2004. Inequality, agro-pastoral exchanges, and soil fertility gradients in southern Mali. Agric. Ecosyst. Environ. 105, 353–372.

Rotich, D.K., Ogaro, V.N., Wabuile, E., Mulamula, H.H.A., Wanjala, C.M.M., Defoer, T., 1999. Participatory characterisation and on-farm testing in Mutsulio village, Kakamega District. Pilot project on soil fertility replenishment and recapitalisation in Western Kenya, report no. 11. Kenya Agricultural Research Institute, Kakamega, Kenya.

Ruthenberg, H., 1980. Farming Systems in the Tropics, third ed. Clarendon Press, Oxford.

Scoones, I., Toulmin, C., 1999. Soil nutrient budgets and balances: what use for policy? Managing African Soils no. 6, 23 pp.

Shepherd, K.D., Walsh, M.G., 2002. Development of reflectance spectral libraries for characterization of soil properties. Soil Sci. Soc. Am. J. 66, 988–998.

Shepherd, K.D., Palm, C.A., Gachengo, C.N., Vanlauwe, B., 2003. Rapid characterization of organic resource quality for soil and livestock management in tropical agroecosystems using near-infrared spectroscopy. Agron. J. 95, 1314–1322.

Smaling, E.M.A., Nandwa, S.M., Janssen, B.H., 1997. Soil fertility in Africa is at stake. In: Buresh, R.J., Sanchez, P.A. (Eds.), Replenishing Soil Fertility in Africa. ASSA, CSSA, SSSA, Wisconsin, pp. 47–61.

Smaling, E.M.A., Fresco, L.O., De Jager, A., 1996. Classifying and monitoring soil nutrient stocks and flows in African agriculture. Ambio 25, 492–496.

Soule, M.J., Shepherd, K.D., 2000. An ecological and economic analysis of phosphorus replenishment for Vihiga division, western Kenya. Agric. Syst. 64, 83–98.

Tiessen, H., Billo, D., Van Oosterhout, S., 2000. Organic soil fertility management in family agriculture of Zimbabwe. In: Martins, M., Tiessen, H., Vlek, P.L.G. (Eds.), Managing Organic Matter in Tropical Soils. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 225–229.

Tittonell, P., 2003. Soil fertility gradients in smallholder farms of western Kenya. Their origin, magnitude and importance. Quantitative approaches in system analysis no. 25. The C.T. de Wit Graduate School for Production Ecology & Resource Conservation, in co-operation with the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), Wageningen, 233 pp., ISBN 90-6754-713-1.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Giller, K.E., 2005a. Estimating yields of tropical maize genotypes from non-destructive, on-farm plant morphological measurements. Agric. Ecosyst. Environ. 105, 213–220.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E., Giller, K.E., 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity at region and farm scale. Agric. Ecosyst. Environ. 110, 149–165.

TSBF, 2001. Folk ecology. Report on the findings of preliminary community interviews and group discussions undertaken on August 29, September 17, 18 and 19, 2001 in Emuhaya, Busia and Teso of Western Kenya. Tropical soil biology and fertility program. Nairobi, Kenya, p. 34.

Van den Bosch, H., De Jager, A., Vlaming, J., 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). II. Tool development. Agric. Ecosyst. Environ. 71, 49–62.

Van Keulen, H., Wolf, J., 1986. Modelling of Agricultural Production: Weather, Soils and Crops. Pudoc, Wageningen, The Netherlands, 479 pp.

Vanlauwe, B., Nwoke, O.C., Diels, J., Sanginga, N., Carsky, R.J., Deckers, J., Merckx, R., 2000a. Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by *Mucuna pruriens*, *Lablab purpureus* and maize. Soil Biol. Biochem. 32, 2063–2077.

Vanlauwe, B., Diels, J., Sanginga, N., Carsky, R.J., Deckers, J., Merckx, R., 2000b. Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by maize to previous herbaceous legume cropping and rock phosphate treatments. Soil Biol. Biochem. 32, 2079–2090.